Postural Control Task Performance of Individuals with Femoroacetabular Impingement Syndrome

Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

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2017

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Abstract

Femoroacetabular impingement (FAI) is the leading cause of hip dysfunction in patients who are young and active. The single leg anterior reach (SLAR) is a common functional task clinically used to measure performance and dynamic postural control of the lower extremity. Kinetic analysis of this clinical task would provide further information regarding the postural control strategies of patients with FAI. **Objective:** To test the hypothesis that patients with FAI will exhibit decreased SLAR performance in the involved limb as compared to the uninvolved limb due to decreased postural control, exhibited by increased center of pressure excursion. **Design:** Cohort study. **Settings:** Movement analysis laboratory. **Participants:** Twenty-six patients clinically and radiographically diagnosed with FAI by a physician; 18 females (165.7 ± 8.2 cm, 66.5 ± 13.7 kg, 34.6 ± 6.8 y) and 8 males (176.6 ± 9.6 cm, 82.0 ± 12.4 kg, 37.5 ± 9.8 y).

**Interventions:** Using a three-dimensional motion capture system and retro-reflective markers placed on the great toe of each foot, maximum SLAR distance was measured as the anterior-posterior distance between each marker at touch-down. Maximum distance was collected for three trials, averaged together, and normalized to limb length. Stance limb center of pressure (CoP) excursion was measured in the anterior-posterior (AP) and medial-lateral (ML) directions using a 40x60cm tri-axial force plate. **Main Outcome Measures:** Mean maximum reach distance was calculated by averaging the maximum value of the three trials for each limb. Center of pressure was calculated in the anterior-posterior and medial-lateral directions as well as total distance traveled throughout the
task. Statistical differences between the involved and uninvolved limb were examined using a one-way ANOVA with an *a-priori* alpha level of 0.05. **Results:** A statistical difference with a moderate effect size (p < 0.001, d=0.328) was noted for mean normalized SLAR distance between the involved (63.1% ± 5.8%) and uninvolved (65.0% ± 5.8%) limbs, with a mean difference of 1.9%. No statistical difference in CoP excursion were noted between the involved and uninvolved limb for any direction (CoP<sub>ML</sub>: p=0.879, CoP<sub>AP</sub>: p=0.895, CoP<sub>Tot</sub>: p=0.881). Mean CoP excursions were:

Involved - AP = 1.54 ± 0.69 m, ML = 1.12 ± .54 m, Total = 2.07 ± 0.95 m; Uninvolved - AP = 1.57 ± 0.76 m, ML = 1.14 ± 0.52 m, Total = 2.12 ± 0.98 m. **Conclusions:** Individuals with FAI demonstrate decreased SLAR performance between limbs despite similar CoP excursion values, suggesting postural control deficits are not the underlying cause of decreased reach performance. Limitations in range of motion or muscle strength associated with FAI may limit SLAR performance, but have little impact on dynamic postural control strategy.
Acknowledgements

Much of my professional training has taken place at The Ohio State University, introducing me to many friends, professors, and mentors along the way. The successes I’ve experienced have in no small way been influenced by the positive impact each of these individuals have had on my development. I’d like to recognize Dr. James Onate and Dr. Mark Merrick for their guidance and support throughout my path in higher education; they have both provided exceptional mentorship and advice at various points in my career. The opportunity to pursue this advanced professional training is a privilege made available to me as a result of the patience and support of my family. The care and involvement my husband and parents provided allowed me the ability to further my career. For these reasons among many more, I’d like to express my gratitude to those listed above; thank you sincerely.
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Chapter 1: Introduction

Femoroacetabular impingement (FAI) is leading cause of hip dysfunction in young, active individuals.\textsuperscript{1,2} FAI is the abnormal articulation between the femoral head and the rim of the acetabulum, leading to increased friction between bone and cartilage.\textsuperscript{1-8} Increased pain, decreased mobility, and decreased balance are common complaints.\textsuperscript{9-11} The clinical and literary awareness of FAI has increased significantly since 2005.\textsuperscript{12} Despite high FAI prevalence, clinical diagnosis and rehabilitative progress remain difficult to measure.

A lack of biomechanical evidence exists upon which to base diagnostic and rehabilitative practices. The majority of published articles regarding FAI have been surgical or radiographic in nature, and those examining rehabilitative measures are of level 4 & 5 evidence.\textsuperscript{12} Very little evidence exists to guide clinical practice in the diagnosis and rehabilitation of patients with FAI.

The Single Leg Anterior Reach (SLAR) is a functional task commonly used to measure limits of stability and is a portion of the Star Excursion Balance Test.\textsuperscript{13-16} This task may be used clinically for evaluation of initial deficits and as a metric for rehabilitative progression.\textsuperscript{13-16} By performing this task in a laboratory, upon a force plate, additional kinetic information will be gathered. We will measure center of pressure excursion in order to assess postural stability during task performance. Low excursion values are associated with good postural control and higher excursion values are associated with postural control deficits. The purpose of this study is to test the
hypothesis that patients with FAI will exhibit decreased SLAR performance in the involved limb as compared to the uninvolved limb due to decreased postural control, exhibited by increased center of pressure excursion.

**Research Question**

Do individuals with femoroacetabular impingement exhibit bilateral asymmetry when performing a dynamic postural control task?

**Hypothesis**

Decreased maximum reach distance is expected to be reported for the involved limb when compared to the uninvolved limb. Decreased postural control is suspected as the underlying cause for the anticipated performance deficit and will be indicated by increased center of pressure excursion during the task for the involved limb when compared to the uninvolved limb.
List of Definitions

Femoroacetabular Impingement  Abnormal articulation of femur and acetabulum resulting from aspherical femoral head and/or overcoverage of acetabular rim.

Postural Control  The act of achieving, maintaining, or regaining a state of balance in a certain position

Dynamic Postural Control  The ability to maintain a stable balanced position throughout completion of a functional task.

Star Excursion Balance Test  A task measuring dynamic balance in 8 directions from a center point.

Single Leg Anterior Reach  The anterior portion of the Star Excursion Balance Test.

Center of Pressure  A method of measuring postural stability using force platforms.

List of Abbreviations

FAI  Femoroacetabular Impingement

SEBT  Star Excursion Balance Test

SLAR  Single Leg Anterior Reach

COP  Center of Pressure
Chapter 2: Review of Literature

**Diagnosis of FAI**

The presence of a cam lesion is marked by a lack of spherical shape to the femoral head and/or a thickening of the femoral neck. This protrusion of the femoral head-neck junction continually compresses the acetabular rim, especially during hip flexion. This repetitive compression causes trauma to the acetabular rim and ossification of the acetabular labrum.\(^7,12,17-20\) Radiographic imaging is required to confirm this problem, and even then morphological changes may be subtle. Cam impingement lesions affect the anterosuperior aspect of the joint due to the repetitive trauma to the labrum by the misshaped femoral head-neck junction associated with dynamic activity; Figure 1 shows an example of such a deformity.

![Figure 1. Cam deformity; loss of spherocity of the femoral head.](image)
Cam lesions are more prevalent among adolescent and younger adult male athletes, though the reason for this is currently unclear. Some speculate one reason may be sports more commonly played by men as compared to women, as football, hockey, and wrestling are all sports with a high prevalence of symptomatic FAI cam lesions. These sports require repetitive power movements in a flexed hip position, causing increased shear stresses to the femoral physes. It has been suggested that this overloading of the joint causes the bone to protectively respond by increasing mineral density at the stressed location.

A pincer impingement lesion is marked by an abnormal shape of the acetabulum. This malformation may either be due to acetabular retroversion (a backwards rotation of the os coxae), protrusion acetabulae (increased depth of the acetabulum, allowing the femoral head to protrude into the pelvis), or an anterior and/or lateral over coverage (over extension of the acetabulum relative to a normally shaped femoral head).\textsuperscript{3,17,21,22}
Pincer deformity most often causes trauma and wearing away of the labrum and is more common in females than males. Much like the cam lesion, the exact reason is unknown. It is believed that the female hip structure, as designed for childbirth, causes a misalignment of the os coxae. The rotation of the innominate bones may lead to the change in shape or coverage of the femoral head. This type of lesion is marked by significantly reduced hip flexion and pain with extension and rotation.¹⁷

Radiographic signs of cam lesion impingement include an alpha angle of greater than 40° and a head-neck offset of less than 8mm.¹⁸,²³
Figure 3. Alpha angle of 55°.

Alpha angle is measured between the longitudinal axis of the femoral neck and a line connecting the center of the femoral head and the point where the head deviates from a best-fit sphere. The pictured angle shows an alpha angle measurement of 62° and illustrates a positive sign for impingement based upon alpha angle. The radiographic image is taken with an oblique approach, focused through the center of the femoral neck. That center point is the location from which the two vectors are drawn and the distance between is measured. The dotted circle represents the best-fit sphere and the top vector is the point at which the shape of the head-neck junction deviates from that path.
Femoral head-neck offset is the distance between two lines: 1) the line tangent to the femoral head, and 2) the line tangent to the most anterolateral aspect of the femoral neck.

Figure 4. Femoral head-neck offset of 3.1mm.

Figure 4 depicts a femoral head-neck offset of 3.1mm; much smaller than average. An offset of 8mm or less is a positive sign for cam impingement.\textsuperscript{18,23} A more spherical femoral head would produce a much wider separation distance between the head and neck. This calculation is based upon the same film angle as is used for calculating the alpha angle.

Radiographic signs of pincer deformities include a center edge angle of greater than 30° and a positive crossover sign. Figure 5 is a positive lateral center edge angle of
45°. An anterior-posterior radiographic image is taken of the full pelvis and the angle is calculated using the ischial tuberosities as reference guides.

Figure 5. Lateral center edge angle of 45°.

The first angle vector is drawn vertically from the center of the hip joint; perpendicular to the ischial line. The second line, also originating from the hip joint center, is drawn in the direction of the lateral edge of the acetabular rim. In a typically developed acetabulum, the value will be 30° or less; however a positive sign will have a larger angle to the over extension of the rim.\textsuperscript{23,24}

Crossover sign is another positive indication of impingement. A positive crossover sign is marked by the posterior acetabular rim (black line) forming an X with the anterior rim (white line). In a typically developed hip, the posterior rim of the
acetabulum would be lateral to the anterior wall and these two lines would not cross each other. The formation of the X crossover is a result of acetabular retroversion.\textsuperscript{23}

![Image](image.png)

Figure 6. Positive crossover sign.

The severity of retroversion is determined by the vertical location of the crossover. A crossover that occurs in the top third of the acetabulum indicates mild retroversion, where a more severe case would present inferiorly.\textsuperscript{25}

Though there appears to be an increase in awareness, interest, and understanding of FAI, diagnosis still proves to be difficult. FAI is more commonly diagnosed by exclusion, whereby diagnosis is achieved by differential diagnosis procedure and ruling out many other more definitive pathologies first.\textsuperscript{26,27} Common candidate conditions include lumbar pathology, sacroiliac dysfunction, adductor muscle strain, athletic
publagia, femoral neck stress fracture, snapping hip syndrome, and hip osteoarthritis.\textsuperscript{10,11} Due to the vast number of potential pathologies, misdiagnosis is quite common. It has been reported that up to 60\% of surgical FAI cases were originally misdiagnosed.\textsuperscript{10} Prolonged diagnosis is another common issue, with patients going for an average of 7 months without a diagnosis.\textsuperscript{28} The gradual, idiopathic onset of symptoms that go unnoticed or ignored can often cause the development of a secondary disorder. It has been reported that the average individual with FAI will experience 1-3 years of symptoms before seeking treatment.\textsuperscript{4} This secondary injury arises from the compensation adapted to avoid the original problem and it’s often this secondary injury that is more evident and leads to the misdiagnosis.

Pain is the most commonly reported symptom of FAI. The pain is typically described in the groin or lateral hip, and closely followed by anterior thigh and buttock pain.\textsuperscript{9} Pain that worsens with activity, twisting and changing direction, painful prolonged sitting, catching with sit-to-stand activity, difficulty with ascending and/or descending stairs, entering or exiting a care, dyspareunia, and difficulty donning socks and/or shoes are all indicative symptoms of a mechanical issue. Straight plane activities are generally okay, however repetitive stresses, such as with running, case exacerbate symptoms.

Many of the findings associated with FAI can be clinically observed. Individuals with FAI often stand in a position that relieves joint pressure. This position is known as the loose pack position and is characterized by slight hip flexion, abduction, and extension. This position also causes a slight listing to the contralateral side for additional
weight support. Clinical gait analysis may also provide some information about the hip pain. About 51% of people experience a slight limp that many report as unnoticeable. Common gait adaptations are Trendelenberg gait, minimizing stance time on the affected limb, and possible asymmetry. Snapping hip syndrome often co-occurs with FAI. Snapping hip syndrome can either be internal or external snapping hip syndrome. External snapping hip syndrome is caused by a tight iliotibial band snapping over the greater trochanter. This can often be observed from a few feet away. Internal snapping hip syndrome can either caused by a tight iliopsoas tendon or articular damage or catching.

Hip flexion is the most painful range of motion with this type of lesion. Activities such as squatting, bending, and pivoting on a flexed hip exacerbate the condition. Reduced internal rotation suggests arthritis, effusions, slipped capital femoral epiphysis, or muscle contracture, but excessive internal rotation with reduced external rotation suggests femoral anteversion. Any noticeable asymmetries, even if they are within normal limits, may suggest hip pathology. Reduced abduction or adduction may be diminished secondary to antagonistic contracture. Some patients describe positive symptoms of FAI despite showing exceptional ROM (dancers, gymnasts, martial artists, yoga practitioners). In the case of these individuals, their impingement is caused by excessive motion rather than anatomic abnormality. This is also echoed by athletes with long stride lengths (runners, pole vaulters, javelin, etc.) often report symptoms
related to FAI during back leg hyperextension.\textsuperscript{31} This seems contrary to typical anterior FAI; however the hyperextended hip is actually in extreme IR at that point.\textsuperscript{30}

The most characteristic sign of symptom localization is the c-sign.\textsuperscript{28} This is evidenced by the cupping of the hand forming a c just above greater trochanter when describing deep interior joint pain. Manual muscle testing may also help to distinguish nerve or muscle pain from articular pain and should be conducted for all muscle groups: abductors (superior gluteal nerve; L4-S1), adductors (obturator; L2-L4), hip flexors/knee extensors (femoral; L2-L4), hip extensors (inferior gluteal nerve; L5-S2), knee flexors/lower leg muscles (sciatic; L4-S3)\textsuperscript{10} Special tests aren’t sufficient on their own to rule in or rule out diagnosis, but special tests can help indicate further radiographic symptom investigation. The log roll test is performed supine on the table. The examiner moves only the femoral head in relation to the acetabulum. The sensitivity of this test is 59% and the specificity is 32%.\textsuperscript{32} The Impingement test (FADDIR) is named due to its function. The starting position for the FADDIR test is forced flexion, adduction, and internal rotation. This test will cause discomfort with any symptomatic hip. Though the FADDIR test is not specific to FAI, it may be most sensitive indicator of FAI\textsuperscript{10} with a sensitivity ranging from 78-99% and a specificity ranging from 4-25%.\textsuperscript{33-35} Conversely, the FABER test is also named due to its function. This test assess for both SI and hip joint dysfunction. It is usually pretty easy for patients to differentiate location of localized pain.\textsuperscript{10} The sensitivity of the FABER test ranges from 42-81% and the specificity ranges from 18-75%.\textsuperscript{32,34,36} The Hip Scour test is probably the best available
for determining if hip pain is intra- or extra-articular. A positive hip scour test would present with bumps and/or catches indicates FAI\textsuperscript{10} the sensitivity of this test is 50% and the specificity is 29%.\textsuperscript{26,32}

\textit{Femoroacetabular Impingement Epidemiology}

Awareness of FAI has increased significantly in recent years. This is evident by the increased number of publications related to FAI. A 5-fold increase in FAI publications is seen from 2005 to 2010; however the majority of published articles are of level 4 & 5 evidence.\textsuperscript{12} Along with additional literature in the area, a significant rise in clinician recognition and diagnosis of FAI has been noted. An interest in identifying prevalence of FAI has led to a multiple cohort studies, particularly examining younger and athletic populations. 48\% of studies published regarding FAI from 2005-2010 were concerned with therapy and prognosis, reflecting a predictable tendency and interest in wanting to treat FAI in the medical community.\textsuperscript{12}

Kapron et.al. (2011) used radiographic imaging to quantify the prevalence of FAI in asymptomatic athletes.\textsuperscript{23} The anteroposterior and frog-leg radiographic views were used for anterior and lateral inspection of 67 healthy Division I A football players (21±1.9 years). At least one radiographic sign of impingement was seen in 95\% of hips examined; bilateral signs of FAI were seen in 48\% of hips examined.\textsuperscript{23} Each player filled out a questionnaire based upon the Hip Outcome Score survey and nearly every subject reported a score of 90\% or better. \textsuperscript{23}
Agricola et al. (2012) set out to determine the age of onset for cam-type deformity and to examine whether an increased prevalence of FAI was seen in elite youth soccer players as compared to age-matched controls. Eighty-nine boy soccer players between the ages of 12 and 19 years and 92 controls received anteroposterior pelvic and frog-leg lateral hip view x-rays. Positive impingement signs were seen in 26% of soccer players as compared to 17% of controls. Abnormal alpha angles were seen as young as 12 years old in both groups; however, visual prominences were only seen among soccer players (13%). Both groups had evidence of flattening at the head-neck junction but it was more common among the soccer players (53%) compared to the controls (18%).

Philippon et al. (2013) conducted a cohort study to determine how common a large alpha angle was among 61 youth hockey players and 27 youth skiers. The athletes were ages 10-18 years with no hip pain or history of hip surgery and underwent physical examination. It was reported that 75% of ice hockey players versus 42% of skiers had an alpha angle > 55°. Among youth ice hockey players, older players tended to have a larger alpha angle; but, this was not the case among youth skiers. Ninety-three percent of hockey players age 16 to 18 years had an alpha angle > 55° compared to 37% of hockey players aged 10 to 12 years. Hockey players that were 16 to 18 years of age were the only age group to have chondral lesions.

Laborie et al. (2011) examined a much larger cohort. A sample of 2081 subjects (18.6 ± 0.5 years), a subset of a population-based prospective study, was radiographically examined. The purpose of this study was to observed injury prevalence among healthy
Norwegians. Activity level was not recorded, but not limited to high level athletes. Cam lesions were reported in 35.0% of male and 10.2% of female participants; pincer deformity was noted in 34.3% of male and 16.6% of female participants.4

These results suggest that radiographic signs are highly prevalent, are more common in young adult males than young adult women, and occur more often in athletic populations. It may also be implied that high level athletes presenting with hip pain should be evaluated for bony abnormalities to determine if FAI is the underlying cause.

*Functional Assessment of Hip Injury*

Functional performance testing is gaining popularity among clinicians in the assessment and treatment of FAI, as it requires simultaneous control and coordination of multiple segments.37 The increased demand of multi-segment coordination with activity is able to provide a challenge that traditional physical examinations aren’t capable of. This is of particular importance to this younger, more active population. A recent review of functional performance testing of the hip concluded that only the deep squat and the single limb stance tests demonstrated validity for a younger, active population.26,37 Patients with FAI recorded a mean peak squat depth of 41% of their limb length; normal mean peak squat depth is 32% of limb length.18 The single limb stance test reported incredibly high sensitivity (100%) and sensitivity (97.3%) values. A positive test elicits pain in the stance limb prior to the end of the 30-second single limb stance.38 Numerous other tests were reviewed for their reliability statistics. The single leg hop for distance reports .80-96 test-retest reliability39 The Star Excursion Balance Test reported .84-.92
test-retest reliability, but .35-.93 inter-tester reliability. It was also noted that an asymmetry of 4 cm or more increased the risk of lower extremity injury 2.5-fold.\textsuperscript{40} The Single Leg Squat is graded upon a 3 category scale: poor, fair, and good. Participants who were categorized into the poor group had significantly slower abduction muscle activations as compared to the other two groups.\textsuperscript{41} This again suggests that the task itself isn’t providing the challenge, but the method by which the task is completed that is causing dysfunction. The overall conclusion is that though there are many functional tests available for hip function assessment, none show sufficient evidence to justify their inclusion into practice. Many of these tests report high reliability when testing healthy subjects, but little research has been done on pathologic populations.

*Dynamic Postural Control*

Postural control is defined as the ability to maintain the body’s position in space for the purpose of stability and/or orientation.\textsuperscript{42} Proprioceptive control of posture is a complex coordination of sensory, motor, and biomechanical components.\textsuperscript{43} The sensorimotor system is a component of the larger motor control system responsible for maintaining normal joint function and body position. Visual, vestibular, and somatosensory afferent input is gathered from the periphery and sent to the central nervous system (CNS).\textsuperscript{44-46} Proprioception is necessary for accurate and coordinated reactions of the efferent system to the afferent information sent from the periphery regarding the demands of the surrounding environment.\textsuperscript{44}
The visual system is the primary source of sensory information for the proprioceptive control of posture. Peripheral vision aids in body control by providing cues regarding postural position and quick perturbations to the visual field. The vestibular system provides a centering effect. This system works to maintain upright position of the body by: (1) controlling the muscles of the eye during head movement, allowing the visual system to fixate on a stationary point, or (2) by sensing body position by means of the otoliths and the semicircular canal system, which are able to detect linear and rotational movements. The somatosensory system utilizes tactile information provided by mechanoreceptors to sense body position and movement. These receptors are sensitive to tension and stretch, often triggered by perturbation of the system.

Postural control is often referred to as balance, which is defined as the ability to achieve a state of equilibrium by maintaining the body’s center of gravity over the body’s base of support. Postural deviation can be measured using force platforms and calculating center of pressure excursion. Center of pressure is the point that represents the sum of all forces acting to support the body. Movement of this point is used to measure postural sway in either quiet stance or during dynamic task. Center of pressure has proven to be a reliable method for measuring postural control in a variety of populations: healthy, injured, young, elderly. Injury has been shown to negatively affect postural control by increasing center of pressure excursion during dynamic task.
The Star Excursion Balance Test (SEBT) is a functional task designed to clinically measure dynamic postural control. It is a unilateral balance test that requires the testee to toe-touch as far from their base of support as possible in 8 directions (45° separate each direction) while maintaining single limb balance. The test requires the individual to keep their foot flat on the floor, their hands on their hips, and prohibits any weight to be placed on the reach limb during the task. The test was designed to be a low-cost and efficient method for clinical use, as only a flat surface and measuring tape are required for completion. The SEBT consistently reports high test-retest reliability values (.84-.92), however inter-tester reliability values are more variable (.35-.93). It has been noted that a 4 cm or more limb asymmetry increases the risk of lower extremity injury 2.5-fold.

The SEBT has adapted over time as further research has been conducted. It is recommended to normalize the reach distance score to limb length. Prior to this suggestion, men typically outperformed women due to average height differences. A learning effect was discovered with repetition of the task leading to the published suggestion of 4 practice trials prior to recording reach distances. This addition to the test, to be completed in all 8 directions, made the test rather time consuming to complete and less desirable to use clinically. For this reason, further study was done to streamline the test. The SEBT was reduced to 3 directions (anterior, posteriolateral, posteriomedial), making it more efficient and less redundant.
The Single Leg Anterior Reach test uses only the anterior portion of the SEBT. The straight plane nature of this task truly focuses on proximal limb control while reaching, which removes the possibility of confounding factors when examining postural stability of patients with hip injuries. This task was chosen because of its similarity to a single leg squat, a task commonly reported to cause pain in this population. By restricting most accessory motions during the task, a more clear picture of proximal control should be gained through this task.

**Clinical Significance**

An increased prevalence in diagnosis of femoroacetabular impingement syndrome has been in recent years as the result of increased awareness and understanding of the pathology. Femoroacetabular impingement negatively affects the ability of young adults to maintain an active lifestyle. Such prevalence is a contributing factor to the nearly $7.2 billion is spent on over 500,000 hip arthroplasty procedures performed each year in the United States as a result of cartilage degradation.$^{57,58}$ A two-fold rise in hip OA incidence is expected by 2030; 41.1 million adults. Arthroscopic surgical intervention is becoming more common, with the hope of avoiding or delaying the onset of OA. Nearly all patients opting for surgical intervention report a reduction in pain with arthroscopic remodeling, however not all patients are able to return to their pre-symptomatic level of activity.$^{1,59-62}$ These differences suggest patients with symptomatic FAI utilize some sort of compensation strategy for task completion. By observing functional task performance and associated movement patterns, we may identify a modifiable characteristic of the
pathology. Identifying a modifiable variable may serve to improve diagnostic, rehabilitative outcomes, and possibly lower the associated cost of treatment for patients with FAI. This study aims to examine dynamic postural control during a single limb anterior reach task. It is hypothesized that decreased postural control will initiate a measurable reach distance deficit for the injured limb.
Chapter 3: Methods

*Study Design and Subject Recruitment*

A cross-sectional study design was chosen to examine bilateral symmetry in postural control for individuals with femoroacetabular impingement. Bilateral comparison is a primary diagnostic method employed by many clinicians in the evaluation of patients and is the rationale for this study design selection. Twenty-six individuals (169.0 ± 9.9 cm, 71.1 ± 14.9 kg, 35.5 ± 7.7 y) clinically and radiographically diagnosed with unilateral FAI were recruited by a single physician’s practice for participation in this study. Exclusion criteria for this study were any lower extremity injury within the past 6 months, previous history of lower extremity surgery, previous surgical intervention for FAI, vestibular/neurologic impairments, decreased lower extremity sensation, and ages younger than 18 years or older than 49 years. Restrictions based upon injury history were applied to protect against confounding factors due to pain or acquired compensatory strategies. Restrictions based upon vestibular, neurologic, and/or sensory deficits due to their effect on proprioception and postural control. Age restrictions were applied for individuals: (1) younger than 18 years due to their legal inability to provide informed consent for their medical treatment, and (2) older than 49 years because hip arthroplasty is typically favored over hip arthroscopy for individuals 50+ years of age. Appropriate ethical approval was granted prior to the commencement of the study and all participants signed an informed consent form approved by the institutional review board prior to data collection.
**Instrumentation and Research Protocol**

Upon consenting participation, subjects’ limb length was recorded followed by having retro-reflective markers affixed to the skin with double-sided tape. A modified Helen Hayes marker set and a 10-camera three-dimensional camera system (Vicon Motion Systems Ltd., Oxford, UK) were used for motion capture of the lower extremities. Seven rigid marker clusters, consisting of 4 fixed markers, were placed on the thigh and shank of both limbs along with a single marker cluster over the sacrum to mark the pelvis. Individual markers were placed bilaterally over the greater trochanters, anterior superior iliac spines, medial and lateral tibiofemoral joint, medial and lateral malleoli, calcaneus, first and fifth metatarsal heads, and great toes. The anterior-posterior distance between the great toe markers was used to measure maximum reach distance. Kinematic data were collected at 300 Hz.

Participants were instructed in the completion of a maximum anterior reach while maintaining a balanced single limb stance. The stance limb was positioned on an embedded force plate (Bertec Corporation, Columbus, Ohio, USA) in order to measure center of pressure excursion; kinetic data were collected at 1200 Hz. Individuals were instructed to keep their foot flat on the floor and their hands on their hips while the opposite limb was used to maximally reach in the anterior direction without losing control, and to then return to the starting position. Loss of control was marked by the heel or side of the stance foot raising off the ground, removing their hands from their hips, or bearing weight with the reaching limb. If any one of these errors were to occur,
the trial was to be discarded and repeated. Three to five practice trials were performed in order to familiarize the participant with the task. Subjects were then asked to complete three trials for each limb for data recording. The tested limb was indicated by the limb providing support throughout the trial; maximum reach and center of pressure excursion were measured for the tested limb in each trial. The three maximum reach distances for each limb were averaged together to yield a mean maximum reach value. This value was normalized to the limb length for each respective limb and compared bilaterally.

Center of pressure is recorded as a position with an x (anterior-posterior) and y (medial-lateral) coordinate for each frame throughout the SLAR trial. The beginning of a trial was marked from the frame in which the great toe marker of the reach limb is level with the great toe marker of the stance limb prior to the reach; the end of a trial was signified by the return of the great toe marker of the reach limb to level with the great toe marker of the stance limb after performing the maximum reach. Anterior-posterior center of pressure (CoP_{AP}) was calculated as the sum of the x coordinate positions and medial-lateral center of pressure (CoP_{ML}) was calculated as the sum of the y coordinate positions. Total center of pressure excursion (CoP_{Tot}) was calculated as the sum of the linear distance traveled between each x,y coordinate in each frame. Equations for each calculation are shown in Figure 7.
Figure 7. Center of pressure excursion equations in the (a) x axis, (b) y axis, and (c) total excursion.

\[
a. \quad CoP_x = \sum_{i=1}^{n} |x_{i+1} - x_i| \\
b. \quad CoP_y = \sum_{i=1}^{n} |y_{i+1} - y_i| \\
c. \quad CoP_{total} = \sum_{i=1}^{n} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}
\]

Statistical Analysis

Within subject comparisons were conducted between the involved and uninvolved limbs for maximum reach distance, time spent in single limb stance, CoP_{AP}, CoP_{ML}, and CoP_{Tot} using a one-way ANOVA. Alpha level was determined \textit{a priori} and set at \( \alpha \leq 0.05 \). Statistical analyses were conducted using SPSS v.21 (IBM Corporation, Chicago, IL, USA).
Chapter 4: Results

A statistical difference with a moderate effect size (p < 0.001, d=0.328) was noted for mean normalized SLAR distance between the involved (reach distance 63.1% ± 5.8% of limb length) and uninvolved (reach distance 65.0% ± 5.8% of limb length) limbs, with a mean difference of 1.9%. No significant difference in CoP excursion were noted between the involved and uninvolved limb for any direction (CoP_{ML}: p=0.879, CoP_{AP}: p=0.895, CoP_{Tot}: p=0.881) nor for time spent in single limb stance. Mean CoP excursions for the involved limb were: AP = 1.54 ± 0.69 m, ML = 1.12 ± .54 m, Total = 2.07 ± 0.95 m. Mean CoP excursions for the uninvolved limb were: AP = 1.57 ± 0.76 m, ML = 1.14 ± 0.52 m, Total = 2.12 ± 0.98 m. Results are depicted graphically in Figures 8 & 9 and Table 1. Individual reach performance score differences are graphically depicted in Figure 10.
Figure 8. Maximum SLAR distance differences between the involved and uninvolved limbs.

Figure 9. Center of Pressure Excursion values comparing the involved and uninvolved limb in the anterior-posterior, medial-lateral, and total directions.
<table>
<thead>
<tr>
<th></th>
<th>Involved</th>
<th>Uninvolved</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reach Performance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% Limb Length)</td>
<td>63.1 ± 5.8</td>
<td>65.0 ± 5.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td><strong>Sagittal Excursion (m)</strong></td>
<td>1.54 ± 0.69</td>
<td>1.57 ± 0.76</td>
<td>.895</td>
</tr>
<tr>
<td><strong>Frontal Excursion (m)</strong></td>
<td>1.12 ± 0.54</td>
<td>1.14 ± 0.52</td>
<td>.879</td>
</tr>
<tr>
<td><strong>Total Excursion (m)</strong></td>
<td>2.07 ± 0.95</td>
<td>2.12 ± 0.98</td>
<td>.881</td>
</tr>
</tbody>
</table>

Table 1. Data values for between limb comparisons.

Figure 10. Individual difference scores for maximum reach performance of the involved and uninvolved limb within each subject. Line denotes minimum detectable change for the Single Leg Anterior Reach test.
Chapter 5: Discussion

A statistical difference in reach distance of 1.9% of limb length exists in reach performance between the involved and uninvolved side. This difference between sides shows the value of the SLAR as an evaluative measure of performance ability. The SLAR is adequately difficult to elicit decreased performance on the injured side when compared bilaterally, as done clinically in practice settings, in most individuals with FAI. Within subject performance differential scores show an average difference of 2 centimeters. Asymmetrical SLAR values are not commonly seen in healthy individuals. Differences may have been larger had the task not been constrained by ankle range of motion. It has been presented that reach performance of the traditional SLAR task, as originally performed as part of the Star Excursion Balance Test (SEBT), can be limited by a decrease range of motion at the ankle joint. This information was presented after a majority of these data were collected, therefore the SLAR task was directed and performed as per the SEBT. Allowing the participant to lift their heel from the ground and remove their hands from their hips may be a truer test of an individual’s limit of stability, eliciting a wider gap in reach performance. It is possible that an increase in performance differential may elicit a difference in measured center of pressure, but that assertion is not currently supported by the presented data.

The SEBT has been used before in the testing of athletic performance of individuals who previously suffered injuries of the lower extremity, with the anterior reach showing the highest correlation to joint injury above the ankle. It is also
commonly employed by clinicians in the evaluation of the hip joint. The anterior reach portion of the test was chosen as this motion is mostly closely related to a single leg squat, which is more commonly used to assess functional movement of the hip. The a priori expectation was that this test would elicit a performance difference in individuals with known hip deficits and that those deficits would be the result of decreased balance on the injured side. It has been reported that these data show a marked decrease in reach performance, but that balance deficits do not exist as tested. This suggests that the reach differences are likely due to some other biomechanical deficit not yet examined. These deficit may include hip range of motion, muscle strength, or muscle activation pattern. Further investigation into these parameters may yield the cause of the existing deficit.

A secondary analysis of the stance data was conducted in order to examine temporal differences in single limb stance. The hypothesis that performance difference may have resulted from compensatory unloading of the injured limb stemmed from the results of a study published in 2009 by Lewis et. al. They reported that joint loading at the hip during walking gait is inversely related to the effort produced at the ankle. An increased ankle push-off walking strategy was a successful adaptation for reducing the hip joint moment during walking. Subjects were directed to complete the SLAR task by reaching as far forward as possible without lifting their heel, thereby reducing the load bearing capabilities of the ankle plantarflexor muscle group. This restriction placed upon the ankle would likely increase the load bearing responsibilities of the hip, thereby
introducing the possibility of secondary compensation. The next strategy hypothesized was to reduce the time spent in single limb stance, thereby reducing the load bearing requirements of the hip. Bilateral comparison yielded no significant difference in temporal parameters of single limb stance; suggesting the hypothesized compensatory strategy is non-existent.

Individuals with FAI demonstrate decreased SLAR performance between limbs despite similar CoP excursion values, suggesting postural control deficits are not the underlying cause of decreased reach performance. Limitations in range of motion or muscle strength associated with FAI may limit SLAR performance, but have little impact on dynamic postural control strategy.
Reference List

14. Clagg S, Paterno MV, Hewett TE, Schmitt LC. Performance on the modified star excursion balance test at the time of return to sport following anterior cruciate ligament...


